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AIR-SIDE PERFORMANCE OF FLAT-TUBE LOUVER-FIN HEAT EXCHANGERS UNDER WET CONDITIONS: WET-SURFACE MULTIPLIERS FOR COLBURN *j*- AND *f*-FACTORS

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ABSTRACT

Empirical correlations for the air-side thermal-hydraulic performance of flat-tube, louver-fin heat exchangers under wet conditions are developed in terms of wet-surface multipliers. Experimental database of dry and wet air-side performance has been compiled from related works in the literature. Important design parameters are identified and used in the correlations. The benefits of wet-surface multipliers in comparison to independent wet *j*- and *f*-factor correlations are discussed. An alternative data modeling approach is briefly introduced and compared with the conventional correlations.

1. INTRODUCTION

Air-side design requirements on heat exchangers include thermodynamic efficiency, manufacturing cost, component size, and air quality. Heat exchangers with flat tubes and louver fins are widely used due to high efficiency and reduced size. However, effective management of condensate retention and drainage has become a significant challenge as serious performance degradation can occur with this type of heat exchangers in comparison to the conventional round-tube geometry. For example, a typical flat-tube heat exchanger with serpentine louver fins (see Figure 1) can retain a substantially larger amount of water than a comparable round-tube heat exchanger. Recent experimental data indicate that the optimal designs of flat-tube, louver-fin heat exchangers are different for dry and wet conditions. In order to achieve good performance for both conditions or to optimize the design for known operating conditions, an accurate prediction of the air-side performance under dry and wet conditions is desired.

In comparison to dry surface conditions, studies on the thermal-hydraulic performance of flat-tube louver-fin heat exchangers under wet conditions are very limited in the literature. Goodremote and Hartfield (1985) reported reduced pressure drop and unaffected heat transfer by hydrophilic coating. Chiou et al. (1994) tested 2 brazed aluminum automotive evaporators under dry and wet conditions. Unfortunately, their experimental data appear incompatible with other studies due to the wet-surface fin efficiency calculation method (McQuiston, 1975) which was later shown to have dependence on relative humidity (Wu and Bong, 1994). McLaughlin and Webb (2000) reported a significant decrease of heat transfer (50%) and pressure drop (25%) occurred under wet condition occurred for louver pitch of 1.1 mm, while much smaller change in heat transfer and pressure drop was observed for the 1.3 mm geometry. They attributed these differences to an increased possibility of louver bridging for a smaller louver pitch. A hydrophilic coating increased heat transfer by 25% but showed insignificant impact on pressure drop in contrast to the observation by Goodremote and Hartfield. Kaiser and Jacobi (2000) also observed decreased sensible heat transfer coefficient under steady condensing conditions. Smaller louver pitch showed more decease of heat transfer under wet conditions—they attributed this to the higher propensity of condensate louver bridging, in agreement with McLaughlin and Webb. Tang and Jacobi (2001) also reported that the decrease of air-side heat transfer and the increase of pressure drop were substantial under wet conditions. They found that a larger fin pitch reduces the increase of pressure drop under wet conditions. In these studies (Kaiser and Jacobi, 2000; Tang and Jacobi, 2001), heat exchangers with less steady-state condensate retention showed a tendency to give better heat transfer and pressure drop performance. Recently, Kim and Bullard (2002a; 2002b) found that both sensible heat transfer and pressure drop increased for a large louver angle, indicating less condensate bridges. Kim and Bullard reported that the pressure drop always increased (up to 100%) under wet conditions. On the other hand, sensible heat transfer coefficient decreased (~30%) or increased (~60%) depending on geometrical and operating conditions. The increased sensible heat transfer occurred particularly for a large louver angle (27°) and small fin pitches (1.0, 1.2 mm).

In the above studies, decreased sensible heat transfer and increased pressure drop frequently occurred under wet conditions. In some cases, however, increased sensible heat transfer and decreased pressure drop have been observed. The trends of experimental data in the literature are often case-dependent and it is difficult to generalize the parametric effects. Because of the inter-dependence of parameters, different behaviors can manifest depending on the parametric configurations. Also, true discrepancies (*e.g.* experimental errors) can occur from the difficulties in experimentation and data reduction, and negligence of important parameters. However, in general, the literature suggests that the louver geometry has a strong impact on the wet air-side performance characteristics. Hydrophilic coatings can make noticeable changes in heat transfer and pressure drop—this indicates that the wettability of air-side surface is an important parameter to wet performance. The most critical parameters to the wet performance of flat-tube louver-fin heat exchangers identified in the literature are: louver pitch, louver angle, fin pitch, and surface wettability (or contact angles). Other important parameters may be un-louvered fin length, air-flow depth, fin length, and tube pitch.

In this study, an empirical correlation is developed for wet air-side thermal-hydraulic performance of flat-tube louver-fin heat exchangers in terms of wet-surface multipliers, defined by Equations (1ab). In order to improve general applicability of the correlations, the parameter space was expanded by compiling experimental data from independent studies. Based on Colburn *j*- and *f*-factor correlations under dry conditions, closed-form correlations of wet-surface *j*- and *f*-factors can be obtained.

$$\phi_j = \frac{j_{\mathrm{wet}}}{j_{\mathrm{dry}}} \tag{1a}$$

$$\phi_f = \frac{f_{\mathrm{wet}}}{f_{\mathrm{dry}}} \tag{1b}$$

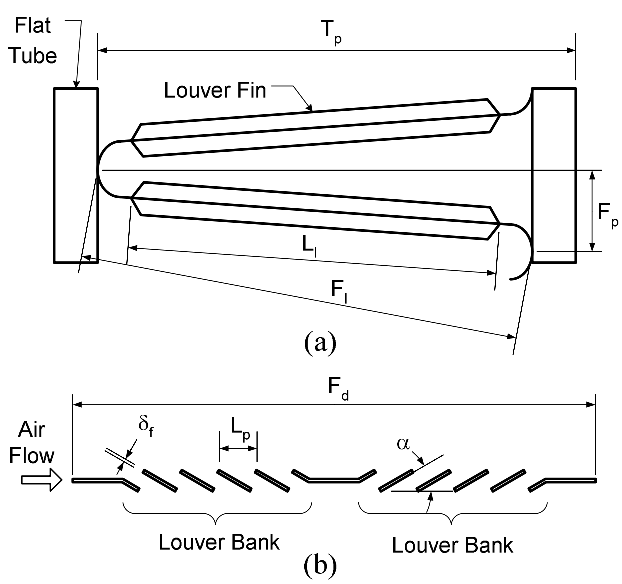


Figure 1: Schematic diagram of a flat-tube, louver-fin heat exchanger
(a) close-up frontal view, (b) cross-sectional view of louver fin

2. DATABASE

An experimental database for air-side heat transfer and pressure drop has been compiled from the literature. A total of 47 samples of flat-tube louver-fin heat exchangers with both dry and wet performance data were identified. The sources include studies by McLaughlin and Webb (2000), Kaiser and Jacobi (2000), Tang and Jacobi (2001), Kim and Bullard (2002a; 2002b), Kim et al. (2002), and Jacobi and Park (2005). The heat exchangers in the present database are listed in Table 1, along with the geometrical parameters. When the original numerical data were not available, figures in the printed articles were scanned and digitized using commercial computer software. Repeated trials using independent software packages showed that the digitized data extraction process was typically reproducible to within 1%. When there was an ambiguity in the plot, the data points were omitted from the database. For consistency, all performance data were cast into the form of Colburn *j* factors and fanning friction factors, defined in Equations (2) and (3), with Reynolds numbers based on louver pitch. For some friction data, the entrance/exit effects were not subtracted in the original data reduction. The difference in *f* factors from this simplification is typically less than 5%, and the original *f* data were used without correction.

$$j = \frac{Nu}{RePr^{1/3}} \tag{2}$$

$$f = \frac{A_{\mathrm{c}}\rho_{\mathrm{m}}}{A\rho_1}\left[\frac{2\rho_1\Delta P}{G_{\mathrm{c}}^{\ 2}} - \left(K_{\mathrm{c}} + 1 - \sigma^2\right) - 2\left(\frac{\rho_1}{\rho_2} - 1\right) + \left(1 - \sigma^2 - K_{\mathrm{e}}\right)\frac{\rho_1}{\rho_2}\right] \tag{3}$$

Two databases of Colburn *j* and *f* factors were obtained, respectively—for dry and wet conditions. The dry data points of individual heat exchanger samples were fitted by either a power-law or a 3rd-order polynomial function of Reynolds number (The overall RMS residual was less than 2%). The wet-surface multipliers were calculated from the ratios of wet-surface data points to dry curve-fit functions. The entire wet-surface multiplier database contains 166 data points for *j* and 196 data points for *f*.

3. WET SURFACE MULTIPLIER CORRELATIONS

3.1 Conventional Correlations

The proposed conventional closed-form correlations for wet-surface multipliers of Colburn *j* and *f* factor are given by Equations (4) and (6), respectively. Basic power-law functional forms were modified to capture detailed parametric effects. Note that all angles should be in radians. The numeric constants are dimensionless and determined such that the RMS relative residual of the entire database, defined by Equation (5), is minimized.

$$\phi_j = C_0\left(Re_{Lp}^{\ C_1} + C_2\left(\frac{L_{\mathrm{p}}}{F_{\mathrm{p}}}\right)^{C_3} Re_{Lp}^{\ C_4}\right)\left(\frac{L_{\mathrm{l}}}{F_{\mathrm{l}}}\right)^{C_6}\sin\left(\alpha + C_7\right)\left(\frac{F_{\mathrm{d}}}{F_{\mathrm{p}}}\right)^{C_8} \cdot\left(\cos\left(\theta_{\mathrm{R}}\right)\right)^{C_9}\left(1-\phi_{j,\mathrm{duct}}\right)+\phi_{j,\mathrm{duct}} \tag{4a}$$

with C0 = 7.229 C1 = -0.6719 C2 = 0.03403 C3 = 0.722 C4 = 0.2527
C5 = 0.01258 C6 = 0.4494 C7 = 0.2509 C8 = 0.05819 C9 = 0.349

and $$\phi_{j,\mathrm{duct}} = 1 - \exp\left(-C_5\left(\frac{F_{\mathrm{p}}}{L_{\mathrm{p}}}\right)^3\right) \tag{4b}$$

minimizing $$\left(RMS_{\mathrm{rel}}\right) = \left[\frac{1}{N}\sum\left(\frac{\phi_{j,\mathrm{cor}}}{\phi_j} - 1\right)^2\right]^{\frac{1}{2}} \tag{5}$$ N = total number of data points

$$\phi_f = \left(D_0 + D_1 \exp\left(D_2 Re_{Lp}\right)\left(\sin(\alpha)\right)^{D_7} \left(\frac{L_p}{F_p}\right)^{D_3} \left(\frac{F_d}{F_p}\right)^{D_8} \right) \left(\frac{F_l}{T_p}\right)^{D_4} \left(\frac{L_p}{F_p}\right)^{D_5} \left(\frac{L_l}{F_l}\right)^{D_6} \tag{6}$$

with D0 = 0.7436 D1 = 0.1317 D2 = -0.003939 D3 = 3.867 D4 = -0.1016
D5 = -0.04680 D6 = -0.8636 D7 = 0.3722 D8 = 0.2931

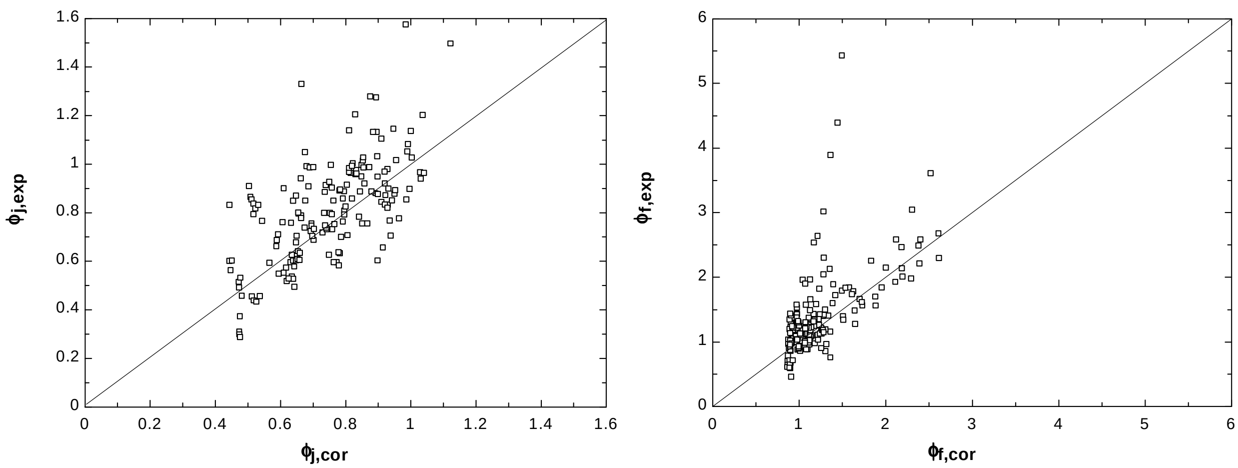


Figure 2: Comparison of the conventional wet-surface multiplier correlations and the experimental data (a) wet-surface multiplier for *j* factor, (b) wet-surface multiplier for *f* factor

The proposed wet-surface multiplier correlations predict the entire database with an RMS error of 21.7% for *j* and 24.4% for *f*. In Figure 2, the wet-surface multipliers predicted by the correlations are compared with the experimental data. For most of the data points, reasonable predictions are obtained.

3.2 Alternative Data Modeling

A typical flat-tube, louver-fin heat exchanger has 9 or more design parameters relevant to the air-side performance, and the individual and combined effects are nonlinear and complex. For this reason, it is difficult to identify an efficient functional form to model the experimental data. As an alternative to the conventional power-law-based correlation, a linear combination of multivariate orthogonal functions can be used to fit wet-surface multiplier data. The orthogonal series approach of nonparametric regression became popular in late 1990s (Christensen, 2001; Efromovich, 1999). This method does not require any specific functional form, and it is useful when the analytical model from the underlying physics is not available. However, in practice, a large size of well-structured database is needed. This method has more flexibility to overcome the difficulty of identifying correct functional form. However, the present application has a risk of over-fitting because of very small amount of available data in comparison to the high degree of freedom. In Equations (7) and (8), the data model, $f(x)$, is represented by a linear expansion of orthogonal base functions, $\psi_j(x)$. The independent variable, x, becomes a vector for multivariate regression.

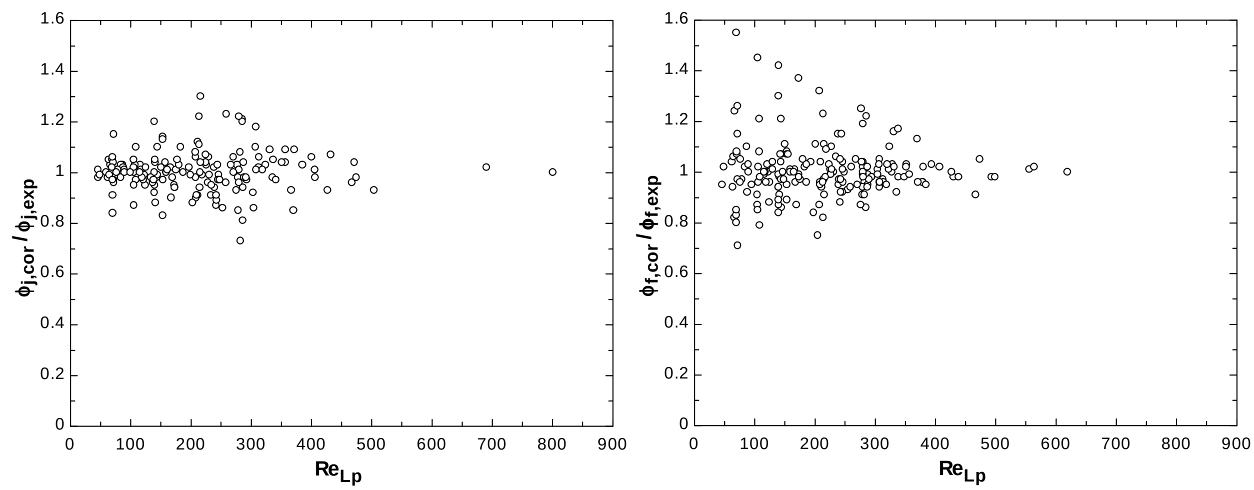
$$f(x) = \sum_{j=0}^{\infty} \beta_j \psi_j(x) \tag{7}$$

$$\beta_j = \frac{\int_0^1 f(x)\psi_j(x)dx}{\int_0^1 \{\psi_j(x)\}^2 dx} \tag{8}$$

In the present application to wet surface multipliers, this method has been adapted for discrete non-uniform data. Normalized Legendre polynomials up to 3rd order—in multivariate form—were used as base functions. A total of 64 base functions were used for both *j* and *f* multipliers. A set of 7 scaled parameters used to fit the experimental data are shown in Table 2. In Figure 3, prediction results by the non-parametric regression method are compared with the experimental wet-surface multiplier data. The RMS relative residuals are 8.2% for *j* multipliers and 11.4% for *f* multipliers. When only the 2nd order base functions (total 36) were applied, the RMS residual for the *f* multipliers became 16.2%.

Table 2: Parameters used in the alternative data regression

	Re_{Lp}	L_p	F_p/L_p	L_l/F_l	α	F_d	F_l/T_p
Scaling	$\exp\left(-Re_{Lp}/500\right)$	Divide by maximum values in the parameter space					



(a) (b)

Figure 3: Comparison of the non-parametric regression models and the experimental data
(a) wet-surface multiplier for *j* factor, (b) wet-surface multiplier for *f* factor

3.3 Comparison and Discussion

Table 3 summarizes the present wet-surface multiplier database and compares the predictive performance of the conventional correlations and the non-parametric regression models. In the present database, under wet conditions, the sensible *j* factor decreases by 19% and the friction factor increases by 38% in average. The standard deviation is much larger for the *f* multipliers than for the *j* multipliers, indicating a greater impact of wet condition on *f* factors. The conventional correlations appear to better predicted the *j* multipliers than the *f* multipliers. On the other hand, when the mean values of the wet-surface multipliers are used as the correlations, the RMS errors are 26% for *j* multipliers and 46% for *f* multipliers. The substantial improvement of accuracy by the conventional correlation for *f* multiplier in comparison to that for *j* multiplier can imply a better predictive capability of the *f*-multiplier correlation. However, if the prediction errors are the result of data scatter from experimental uncertainty, the seeming superiority of *f*-multiplier correlation may be simply due to stronger parametric effects associated with *f* multipliers.

The multivariate non-parametric regression method yields much smaller RMS relative errors in comparison to the conventional correlations. However, since the number of base functions is fairly large (total 64) for the given database (fewer than 200 each for *j* and *f* multipliers), the experimental data may have been over-fitted. The orthogonality of base functions is not preserved in the present parameter space, which contains non-uniformly distributed discrete data points. When some base functions were added or removed, the weight parameters (β_j) of the other base functions changed, showing a non-orthogonal behavior. The present non-parametric regression method can accurately reproduce the data with which it was fitted. However, caution should be taken when predicting a new geometry even within the range of parameters in the database. For geometries outside the parameter space, it is strongly recommended to compare the predictions by both the conventional and the non-parametric regression methods.

The advantage of using wet-surface multipliers instead of independent wet *j* and *f* factor correlations lies in the handling of data with experimental uncertainties, unidentified errors, and inconsistent data reduction methods. The discrepancies in the experimental data among different studies are difficult to reconcile, whereas individual studies often show self-consistent data. The wet-surface multipliers can reduce biases from systematic errors in the experiments and inconsistent data interpretation methods. The present correlation results in Table 3 suggest the existence of considerable scatter in the data. The wettability effect has not been well represented by the database and the correlations. Furthermore, due to the complex nature of condensate retention and drainage in heat exchangers, small geometrical differences may cause a significant change of performance. Aside from the data scatter, the current experimental database is very limited in size and variety to fully represent the effects of all the relevant parameters.

Table 3: Summary of the predictive performance of correlations

	Mean	Standard deviation	RMS_m	RMS_1	RMS_2
ϕ_j	0.81	0.21	0.26	0.21	0.08
ϕ_f	1.38	0.63	0.46	0.24	0.11

RMS_m: when constants (mean values) are used as correlations
RMS_1: by conventional correlations
RMS_2: by non-parametric regression

4. CONCLUSIONS

In this study, empirical correlations for wet-surface multipliers for sensible *j* and *f* factors for flat-tube louver-fin heat exchangers are developed by a conventional form and a non-parametric regression method using experimental database. Important parameters are summarized from the literature and used in the correlations. The conclusions are:

- Generally, the air-side sensible heat transfer decreases and the friction increases under wet conditions
- The louver geometry and surface wettability are important for the wet performance.
- The conventional correlation gives a reasonable prediction of the experimental data.
- The non-parametric regression method improves accuracy of prediction but requires a careful usage.
- Current experimental database does not represent full parametric effects on wet heat exchanger performance.

NOMENCLATURE

F_d	air flow depth	(mm)
F_l	fin length	(mm)
F_p	fin pitch	(mm)
j	Colburn *j* factor	(–)
f	fanning friction factor	(–)
L_l	louver length	(mm)
L_p	louver pitch	(mm)
N_{LB}	number of louver banks	(–)
Re_{Lp}	Reynolds number based on louver pitch	(–)

T_p	tube pitch	(mm)

Greeks

α	louver angle	(deg)
δ_f	fin thickness	(mm)
ϕ_j	wet surface multiplier for *j*	(–)
ϕ_f	wet surface multiplier for *f*	(–)

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Table 1: Geometrical description of heat exchangers in database

Name	L_p [mm]	F_p [mm]	F_l [mm]	L_l [mm]	α [°]	F_d [mm]	T_p [mm]	δ_f [mm]	N_{LB}	θ_A [°]	θ_R [°]
J #1	1.40	1.06	7.93	6.93	27	15.9	9.86	0.10	2	96	30
J #2	1.40	2.12	7.93	6.93	27	27.9	9.86	0.10	2	96	30
J #3	1.40	1.06	7.93	6.93	27	27.9	9.86	0.10	2	96	30
J #4	1.14	5.08	12.43	11.15	29	25.4	14.26	0.11	2	72	10
J #5	1.14	2.12	12.43	11.15	29	25.4	14.26	0.11	2	72	10
J #6	1.14	1.41	12.43	11.15	29	25.4	14.26	0.11	2	72	10
KB #1	1.7	1	8.15	6.4	15	20	10.15	0.1	2	70$^+$	30$^+$
KB #2	1.7	1.2	8.15	6.4	15	20	10.15	0.1	2	70$^+$	30$^+$
KB #3	1.7	1.4	8.15	6.4	15	20	10.15	0.1	2	70$^+$	30$^+$
KB #4	1.7	1	8.15	6.4	27	20	10.15	0.1	2	70$^+$	30$^+$
KB #5	1.7	1.2	8.15	6.4	27	20	10.15	0.1	2	70$^+$	30$^+$
KB #6	1.7	1.4	8.15	6.4	27	20	10.15	0.1	2	70$^+$	30$^+$
KB #7	1.7	1	8.15	6.4	23	16	11.15	0.1	2	70$^+$	30$^+$
KB #8	1.7	1	8.15	6.4	23	20	10.15	0.1	2	70$^+$	30$^+$
KB #9	1.7	1	8.15	6.4	23	24	10.15	0.1	2	70$^+$	30$^+$
KB #10	1.7	1.4	8.15	6.4	23	16	11.15	0.1	2	70$^+$	30$^+$
KB #11	1.7	1.4	8.15	6.4	23	20	10.15	0.1	2	70$^+$	30$^+$
KB #12	1.7	1.4	8.15	6.4	23	24	10.15	0.1	2	70$^+$	30$^+$
KB #13	1.7	1.4	8.15	6.4	25	16	11.15	0.1	2	70$^+$	30$^+$
KB #14	1.7	1.4	8.15	6.4	27	16	11.15	0.1	2	70$^+$	30$^+$
KB #15	1.7	1.4	8.15	6.4	29	16	11.15	0.1	2	70$^+$	30$^+$
KB #16	1.7	1.4	8.15	6.4	19	20	10.15	0.1	2	70$^+$	30$^+$
KB #17	1.7	1.4	8.15	6.4	25	24	10.15	0.1	2	70$^+$	30$^+$
KB #18	1.7	1.4	8.15	6.4	27	24	10.15	0.1	2	70$^+$	30$^+$
KB #19	1.7	1.4	8.15	6.4	29	24	10.15	0.1	2	70$^+$	30$^+$
KSB	1.4	2.1	8.3	6.6	27	27.9	9.9	0.1	2	70$^+$	30$^+$
KJ #1	1.2	1.81	8	6.35	30	58	10.1*	0.1	4$^+$	68	44
KJ #2	1	1.81	8	6.35	36	58	10.1*	0.1	4$^+$	68	44
KJ #3	1	1.81	8	6.35	42	58	10.1*	0.1	4$^+$	68	44
TJ #1	1.03	2.11	9	6.15	30	75	12.0*	0.08	4	82	25
TJ #2	1.33	2.11	11.5	7.93	16	83	15.7*	0.13	4	76	44
TJ #3	1.12	1.81	10	6.74	20	72	12.5*	0.09	4	110	48
TJ #4	1.12	1.81	8	6.35	20	58	13.8*	0.1	4	64	44
TJ #5	1.94	1.81	9	6.35	12	73	11.7*	0.13	4	79	18
TJ #6	1.54	1.81	9.8	7.54	14	92	12.9*	0.15	4	86	45
TJ #7	2.66	1.81	9	6.35	17	92	12.0*	0.1	4	60	34
TJ #8	0.95	1.81	8	5.75	17	64	11.4*	0.09	4	83	25
MW #1	1.1	1.6	8	7	30	50	9.7	0.1	4$^+$	92	72
MW #2	1.1	1.6	8	7	30	50	9.7	0.1	4$^+$	51	17
MW #3	1.3	1.6	8	7	30	50	9.7	0.1	4$^+$	51	17
MW #4	1.3	1.6	8	7	30	60	11	0.1	4$^+$	51	17
MW #5	1.3	2.4	8	7	30	60	11	0.1	4$^+$	51	17

* Estimated from original data
$^+$ Assumed